

# IS PLANETARY MIGRATION INEVITABLE?

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**Abstract.** According to current theories, tidal interactions between a disk and an embedded planet may lead to the rapid migration of the protoplanet on a timescale shorter than the disk lifetime or estimated planetary formation timescales. Therefore, planets can form only if there is a mechanism to hold at least some of the cores back on their way in. Once a giant planet has assembled, there also has to be a mechanism to prevent it from migrating down to the disk center. This paper reviews the different mechanisms that have been proposed to stop or slow down migration.

## 1. Introduction

Almost 20% of the extrasolar planets detected so far orbit at a distance between 0.038 and 0.1 astronomical unit (au) from their host star.

It is very unlikely that these short-period giant planets, also called 'hot Jupiters', have formed *in situ*. In most of the standard disk models, temperatures at around 0.05 au are larger than 1500 K (Bell et al. 1995; Papaloizou & Terquem 1999), preventing the condensation of rocky material and therefore the accretion of a solid core there. Even if models with lower temperatures are considered, giant planets may form in close orbits according to the core accretion model only if the disk surface density is rather large and the accretion process very efficient (Bodenheimer et al. 2000; Ikoma et al. 2001). This is because at 0.05 au a solid core of about 40 earth masses has to be assembled before a massive gaseous envelope can be accreted (Papaloizou & Terquem 1999; Bodenheimer et al. 2000). More likely, the hot Jupiters have formed further away in the protoplanetary nebula and have migrated down to small orbital distances. It is also possible that migration and formation were concurrent (Papaloizou & Terquem 1999).

So far, three mechanisms have been proposed to explain the location of planets at very short orbital distances. One of them relies on the gravitational interaction between two giant planets, which may lead to orbit crossing and to the ejection of one planet while the other is left in a smaller orbit (Rasio & Ford 1996; Weiden-schilling & Marzari 1996). However, this mechanism cannot reproduce the orbital characteristics of the extrasolar planets observed so far. Another mechanism is the so-called 'migration instability' (Murray et al. 1998; Malhotra 1993). It involves resonant interactions between the planet and planetesimals located inside its orbit



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which lead to the ejection of a fraction of them while simultaneously causing the planet to migrate inward. Such interactions require a very massive disk to move a Jupiter mass planet from several astronomical units down to very small radii, as there has to be at least on the order of a Jupiter mass of planetesimals inside the orbit of the planet. Such a massive disk is unlikely and furthermore it would be only marginally gravitationally stable. The third and most efficient mechanism involves the tidal interaction between the protoplanet and the gas in the surrounding protoplanetary nebula (Goldreich & Tremaine 1979, 1980; Lin & Papaloizou 1979, 1993 and references therein; Papaloizou & Lin 1984; Ward 1986, 1997a). Here again the protoplanet can move significantly only if there is at least a comparable mass of gas within a radius comparable to that of its orbit. However this is not a problem since this amount of gas is needed anyway in the first place to form the planet.

Note that hot Jupiters can also be produced by the dynamical relaxation of a population of planets on inclined orbits, formed through gravitational instabilities of a circumstellar envelope or a thick disk (Papaloizou & Terquem 2001). However, if objects as heavy as  $\tau$ -Boo may be produced *via* fragmentation, it is unlikely that lower mass objects would form that way.

Tidal interaction between a disk and a planet may lead to two different types of migration (Ward 1997a; Terquem et al. 2000 and references therein). Cores with masses up to about  $10 M_{\oplus}$  interact linearly with the surrounding nebula and migrate inward *relative* to the gas (type I migration). Planets with masses at least comparable to that of Jupiter interact nonlinearly with the disk and may open up a gap (Goldreich & Tremaine 1980; Lin & Papaloizou 1979, 1993 and references therein). The planet is then locked into the angular momentum transport process of the disk, and migrates *with* the gas at a rate controlled by the disk viscous timescale (type II migration). The direction of type II migration is that of the viscous diffusion of the disk. Therefore it is inward except in the outer parts of the disk which diffuse outward.

The drift timescale for a planet of mass  $M_{\text{pl}}$  undergoing type I migration in a uniform disk is (Ward 1986, 1997a):

$$\tau_{\text{I}}(\text{yr}) \sim 10^8 \left( \frac{M_{\text{pl}}}{M_{\oplus}} \right)^{-1} \left( \frac{\Sigma}{\text{g cm}^{-2}} \right)^{-1} \left( \frac{r}{\text{au}} \right)^{-1/2} \times 10^2 \left( \frac{H}{r} \right)^2 \quad (1)$$

where  $\Sigma$  is the disk surface density,  $r$  is the distance to the central star, and  $H$  is the disk semithickness. It is assumed here that the torque exerted by the material which corotates with the perturbation can be neglected.

For type II migration, the characteristic orbital decay timescale is the disk viscous timescale:

$$\tau_{\text{II}}(\text{yr}) = \frac{1}{3\alpha} \left( \frac{r}{H} \right)^2 \Omega^{-1} = 0.05 \frac{1}{\alpha} \left( \frac{r}{H} \right)^2 \left( \frac{r}{\text{AU}} \right)^{3/2} \quad (2)$$

where  $\alpha$  is the standard Shakura & Sunyaev (1973)'s parameter and  $\Omega$  is the angular velocity at radius  $r$ .

It has recently been shown by Masset & Papaloizou (2003) that a planet in the intermediate mass range embedded in a disk massive enough may undergo a runaway migration. This typically happens for Saturn-sized giant planets embedded in disks with a mass several times the minimum mass of the solar nebula. The timescale for runaway migration can be much shorter than that for type I or type II migration.

For typical disk parameters, the timescales given above are much shorter than the disk lifetime or estimated planetary formation timescales. Therefore, planets can form only if there is a mechanism to hold at least some of the cores back on their way in. Once a giant planet has assembled, there also has to be a mechanism to prevent it from migrating down to the disk center. We now review the different mechanisms that have been proposed to slow down, stop or reverse migration.

## 2. Stopping type I migration

### 2.1. STOPPING TYPE I MIGRATION AT SMALL RADII

Cores undergoing orbital decay due to type I migration would stop before plunging onto the star if the disk had an inner (magnetospheric) cavity. Merger of incoming cores and subsequent accretion of a massive gaseous atmosphere could then produce a hot Jupiter *in situ* (Ward 1997b, Papaloizou & Terquem 1999). However, the extent of magnetospheric cavities is very limited, and therefore this mechanism cannot account for the presence of planets orbiting further away from the central star. For these planets to be assembled, type I migration has to be either avoided or halted. Type I migration would not take place if the interaction between the core and the disk could become nonlinear with a resulting gap formation. However, as discussed by Terquem et al. (2000), this situation is unlikely. We now review the mechanisms that have been proposed to halt or reverse type I migration.

### 2.2. MIGRATION OF PLANETS ON ECCENTRIC ORBITS

The migration timescale given by equation (1) applies to a planet on a circular orbit. Papaloizou & Larwood (2000) have investigated the case of a planetary core on an eccentric orbit (in an axisymmetric disk) with an eccentricity  $e$  significantly larger than the disk aspect ratio  $H/r$ . They found that the direction of orbital migration reverses for fixed eccentricity  $e > 1.1H/r$ . This is because the core spends more time near apocenter, where it is accelerated by the surrounding gas, than near pericenter, where it is decelerated. In general, the interaction between the core and the disk leads to eccentricity damping (Goldreich & Tremaine 1980). However, Papaloizou & Larwood (2000) showed that a significant eccentricity could be maintained by gravitational interactions with other cores. Papaloizou (2002) further studied the case of a core embedded in an eccentric disk. He showed that migration may be significantly reduced or even reverse from inward to outward when the eccentricity

of the orbit of the core significantly exceeds that of the disk when that is large compared to  $H/r$  and the density profile is favorable. In some cases, such a high orbital eccentricity may be an equilibrium solution, and therefore suffers no damping.

### 2.3. STOPPING MIGRATION BY A TOROIDAL MAGNETIC FIELD

Terquem (2003) has investigated the effect of a toroidal magnetic field on type I migration for a planet on a circular orbit. When a field is present, in contrast to the nonmagnetic case, there is no singularity at the corotation radius, where the frequency of the perturbation matches the orbital frequency. However, all fluid perturbations are singular at the so-called *magnetic resonances*, where the Doppler shifted frequency of the perturbation matches that of a slow MHD wave propagating along the field line. There are two such resonances, located on each side of the planet's orbit and within the Lindblad resonances. Like in the nonmagnetic case, waves propagate outside the Lindblad resonances. But they also propagate in a restricted region around the magnetic resonances.

The magnetic resonances contribute to a significant global torque which, like the Lindblad torque, is negative (positive) inside (outside) the planet's orbit. Since these resonances are closer to the planet than the Lindblad resonances, they couple more strongly to the tidal potential and the torque they contribute dominates over the Lindblad torque if the magnetic field is large enough. In addition, if  $\beta \equiv c^2/v_A^2$ , where  $c$  is the sound speed and  $v_A$  the Alfvén velocity, increases fast enough with radius, the outer magnetic resonance becomes less important (it disappears altogether when there is no magnetic field outside the planet's orbit) and the total torque is then negative, dominated by the inner magnetic resonance. This leads to outward migration of the planet.

The amount by which  $\beta$  has to increase outward for the total torque exerted on the disk to be negative depends mainly on the magnitude of  $\beta$ . It was found that, for  $\beta = 1$  or 100 at corotation, the torque exerted on the disk is negative when  $\beta$  increases at least as fast as  $r^2$  or  $r^4$ , respectively.

The migration timescales that correspond to the torques calculated when a magnetic field is present are rather short. The orbital decay timescale of a planet of mass  $M_{\text{pl}}$  at radius  $r_p$  is  $\tau = M_p r_p^2 \Omega_p / |T|$ , where  $T$  is the torque exerted by the planet on the disk and  $\Omega_p$  is the angular velocity at radius  $r_p$ . This gives:

$$\tau(\text{yr}) = 4.3 \times 10^9 \left( \frac{M_{\text{pl}}}{M_{\oplus}} \right)^{-1} \left( \frac{\Sigma_p}{100 \text{ g cm}^{-2}} \right)^{-1} \left( \frac{r_p}{1 \text{ au}} \right)^{-1/2} \left( \frac{|T|}{\Sigma_p r_p^4 \Omega_p^2} \right)^{-1} \quad (3)$$

where  $\Sigma_p$  is the disk surface density at radius  $r_p$ . In a standard disk model,  $\Sigma \sim 100\text{--}10^3 \text{ g cm}^{-2}$  at 1 au (see, for instance, Papaloizou & Terquem 1999). Therefore,  $\tau \sim 10^5\text{--}10^6 \text{ yr}$  for a one earth mass planet at 1 au in a nonmagnetic disk, as  $|T|/(\Sigma_p r_p^4 \Omega_p^2) \sim 10^3$  in that case (see fig. 9 from Terquem 2003). This is in agreement with Ward (1986, 1997a, see eq. [1] above). In a magnetic disk,  $|T|/(\Sigma_p r_p^4 \Omega_p^2)$

may become larger (see fig. 9 from Terquem 2003) leading to an even shorter migration timescale. However, it is important to keep in mind that these timescales are *local*. Once the planet migrates outward out of the region where  $\beta$  increases with radius, it may enter a region where  $\beta$  behaves differently and then resume inward migration for instance.

The calculations summarized here indicate that a planet migrating inward through a nonmagnetized region of a disk would stall when reaching a magnetized region. It would then be able to grow to become a terrestrial planet or the core of a giant planet. We are also led to speculate that in a turbulent magnetized disk in which the large scale field structure changes sufficiently slowly a planet may alternate between inward and outward migration, depending on the gradients of the field encountered. Its migration could then become diffusive, or be limited only to small scales.

### 3. Stopping type II migration

#### 3.1. STOPPING TYPE II MIGRATION AT SMALL RADII

Like cores undergoing type I migration, planets subject to type II migration would stop before falling onto the star if they entered a magnetospheric cavity. Tidal interaction with a rapidly rotating star would also halt planet orbital decay at a few stellar radii (where the interaction becomes significant; see Lin et al. 2000 and references therein). Both of these mechanisms have been put forth to account for the present location of the planet around 51 Pegasi (Lin et al. 1996), and to explain the location of hot Jupiters more generally.

A planet overflowing its Roche lobe and losing part of its mass to the central star would also halt at small radii. This is because during the transfer of mass the planet moves outward to conserve the angular momentum of the system (Trilling et al. 1998). The planet stops at the location where its physical radius is equal to its Roche radius. Recent observations of atomic hydrogen absorption in the stellar Lyman  $\alpha$  line during three transits of the planet HD209458b suggest that hydrogen atoms are escaping the planetary atmosphere (Vidal-Madjar et al. 2003).

#### 3.2. “THE LAST OF THE MOHICANS”...

The mechanisms reviewed above cannot account for the presence of giant planets orbiting their parent star at distances larger than about a tenth of an au.

It has been suggested that migration of a giant planet could be stopped at any radius if migration and disk dissipation were concurrent (Trilling et al. 1998, 2002). Note that a massive planet can suffer significant orbital decay only if the mass of gas in its vicinity is comparable to the mass of the planet itself. If the disk is significantly less massive, there is not enough gas around the planet to absorb its angular momentum, and migration is slowed down (Ivanov et al. 1999). If the disk

dissipates while migration is taking place, then the drift timescale may increase in such a way that the planet stalls at some finite radius. Note however that this requires very fine tuning of the parameters (disk mass, disk lifetime etc.), as for a given disk mass the migration timescale decreases as the orbital radius decreases (see eq.[2] above). Also, a major problem with this mechanism is to explain how the disk dissipates. Within this scenario, there is initially enough gas in the disk to push the planet down to some orbital radius. For typical disk parameters, only part of this gas may be accreted by the planet or leak through the gap to be accreted onto the star (Bryden et al. 1999, Kley 1999). It is therefore not clear how the gas disappears.

A giant planet could survive if after it formed there were not enough material left in the disk for significant migration to occur. It has been suggested that a series of giant planets could actually assemble in the disk and disappear onto the star (Gonzalez 1997, Laughlin & Adams 1997). Then at some point the disk mass may be such that one more planet can be formed but not migrate (Lin 1997). This survivor is sometimes referred to as the last of the Mohicans.

### 3.3. PLANETS LOCKED IN RESONANCES

Within the context of several planets forming in a disk, another scenario has been suggested to occur when the migration of the innermost planet is stopped by either the star's tidal barrier or a magnetospheric cavity. In that case, a second planet approaching the star would stop when entering a low order resonance with the innermost planet, i.e. when the mean motions of the two planets become commensurate. As shown by Goldreich (1965) in the context of our Solar system, such commensurabilities are stable because angular momentum is secularly transferred between the different objects in just the correct proportion to keep the mean motions commensurate. In the context of the planetary system discussed here, the angular momentum would be transferred from the central star to the innermost planet then to the ring of material trapped between this planet and the next one, then from this ring to the next planet, and so on until the angular momentum is transferred to the disk outer part. The evolution of the central star may cause the whole system to migrate either inward or outward, but the planets remain locked into the resonances (Lin 1997).

Like with the scenario discussed in the previous subsection, a major problem here is to explain how the disk material trapped in between the different planets eventually disappears.

Resonant trapping of planets can also lead to a reversal of type II migration. This happens when a giant planet (e.g. Jupiter) migrating inward captures into the 2:3 resonance a lighter outer giant planet (e.g. Saturn, Masset & Snellgrove 2001). The gaps that the two planets open in the disk then overlap, and the imbalance between the torque exerted at Jupiter's inner Lindblad resonance and that exerted at Saturn's outer Lindblad resonance causes the whole system to migrate outward.

This outward migration is accompanied by an increased mass flow through the overlapping gaps, as the angular momentum gained by the planets is lost by the disk.

#### 4. Conclusions

We have reviewed the different mechanisms which have been proposed to slow down, halt or reverse inward orbital migration. When the interaction between the disk and the planet(s) is linear, orbital decay can be stopped if a magnetic field is present in the disk or if the planets are on sufficiently eccentric orbits. For a non-linear interaction, no general mechanism has been shown to prevent orbital decay of an isolated planet. Whether type II migration occurs or not may just depend on the mass of gas left in the disk after the planet forms.

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